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NATURE AND POSSIBLE CAUSES OF THE NORTHEASTERN UNITED STATES DROUGHT DURING 1962–65

JEROME NAMIAS

Extended Forecast Division, Weather Bureau, Environmental Science Services Administration, Washington, D.C.

ABSTRACT

During the past 4 years noteworthy weather fluctuations of a persistent kind have occurred over large portions of the United States, the most prominent of which have been the deficiency in precipitation over the Northeast and the excess over the Southwest and the Northern Plains. The nature of these abnormalities is described with the help of seasonal frequency distributions of precipitation determined for 40 climatologically homogeneous areas of the country. From this and other material it is shown that the Northeast drought has been largely a spring and summer phenomenon at the same time when abundant rains occurred over the Northern Plains and Far Southwest.

The large-scale upper-air currents favoring or inhibiting precipitation through interactions with air masses and storms are next described. The most consistent year-to-year feature of these upper winds in the quadrennial has been the persistence of one southward dip in the westerlies just off the eastern seaboard and another over the Far Southwest.

A hypothesis is proposed for the cause of the aberrant upper-wind currents which considers the atmosphere and ocean as a complex coupled system. Abnormalities of sea-surface temperature are created by anomalous surface wind drag and by extraction of heat by anomalous air masses. The ocean thus serves as a reservoir whose heat transfer affects sequences of atmospheric systems. An attempt is made to show that a feedback system of this type has been operating efficiently during the past 4 years so as to produce the observed anomalous weather patterns.

1. INTRODUCTION

Climatic fluctuations are continually taking place over large areas of the world. These fluctuations may be of the order of a week, a month, a season, a year, a decade, a century, and upward to millennia. Meteorologists recognize these fluctuations as integral parts of the total weather picture. If there were no substantial deviations from normal of weather conditions in some portions of the Nation during a month or season the meteorologist would indeed be astonished. In short, abnormality of cumulative weather is in fact a "normal" condition. Thus, winters over the United States in different years vary in their characteristics.

The meteorological time series which express these phenomena are statistically coherent. The coherence exists not only between successive days but, equally important, exists also in a persistent recurrence of similar weather regimes during a specified period. These climatic fluctuations, particularly those which last from a season to several years, have always attracted the attention of the layman as well as the meteorologist, because they are of immense importance to various segments of the American economy.

The most recent climatic fluctuations with which the general public is now familiar are the drought which has plagued the Northeast for the past 4 years, and the simultaneous superabundance of precipitation over the Far Southwest and the Northern Plains.

The purpose of this paper is to describe certain features of this climatic fluctuation in terms of rainfall and temperature patterns, to relate these to the prevailing large-scale air currents in the atmosphere well above the earth's surface, and to propose a theory which might explain how these abnormal conditions, particularly over the Northeast, have been generated and maintained.

2. ABNORMALITY OF CLIMATIC PRECIPITATION PATTERN OVER THE UNITED STATES 1962–65

The facts of the recent 4-yr. climatic fluctuation which call for an explanation may be illuminated by maps which show the general nature of the precipitation for the period as a whole and for each of the four seasons. Therefore, seasonal precipitation totals have been computed for roughly 170 stations over the United States and plotted on national base maps. These data have been analyzed in terms of three equally likely precipitation categories—light, moderate, and heavy. The numerical limits which define these classes have been determined from a statistical analysis of roughly 30 years of seasonal precipitation amounts. Of course, the ranges of precipitation which make up light, moderate, or heavy precipitation vary from area to area and from season to season.

The analysis for spring 1965 is shown in figure 1. The precipitation characteristics of the 16 seasons comprising the period December 1961 through November 1965 have been summarized with the help of a number of charts. Winter is defined as December, January, and February; spring as March, April, and May; etc.

Figure 2 indicates 40 circular areas of the country for which the frequencies of the three classes of precipitation were counted. These areas, taken from a work by Klein [1], are 230 mi. in diameter and climatologically homogeneous. For each season the predominant category of precipitation in each area was recorded. The summation for the seasons of the 4 years 1962–65 is given in figure 3 where rows represent successive seasons from winter (at the top) to spring, summer, and fall. Columns represent successive years beginning with 1962. A glance at figure 3 quickly reveals the prevalence of the heavy precipitation category over the Far Southwest and the Northern Plains. I have summarized the number of seasons characterized by light, moderate, or heavy precipitation in each of the 40 areas in figure 4, and have roughly outlined coherent areas of prevalence of each of the three categories, as indicated in the legend. This figure brings into sharp focus the prevalence of light precipitation over the Northeast and heavy precipitation over the Far Southwest and the Northern Plains. A secondary area of predominantly light precipitation can be observed over western Texas, and a secondary area of moderate to heavy precipitation, over Alabama and eastern Tennessee. For this quadrennial New York City recorded only 60 percent of its normal precipitation, while Winslow, Ariz., had 112 percent and Williston, N. Dak., 124 percent.

If the frequency chart is partitioned by seasons, but not by years, we obtain the maps shown in figure 5. These show that the Northeast drought has been largely a spring and summer—not an all-year—phenomenon. The heavy rains have occurred mainly during spring and summer in the Northern Plains and summer and fall in the Far Southwest. Table 1 indicates the percentage of normal precipitation observed at New York City, Winslow, Ariz., and Williston, N. Dak., during each of the four seasons.

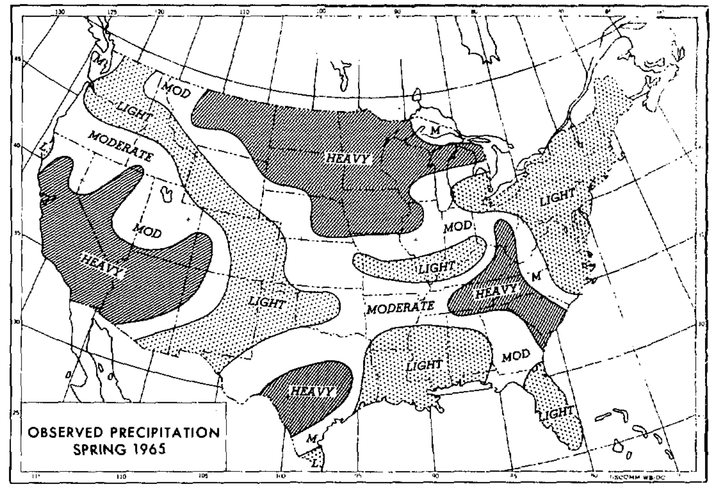

FIGURE 1.—Precipitation classes observed for spring (March, April, May) 1965 in terms of light (stipled), moderate (unshaded), and heavy (shaded). The ranges for these equally likely classes have been determined from the average of precipitation records for the springs of some 30 years.

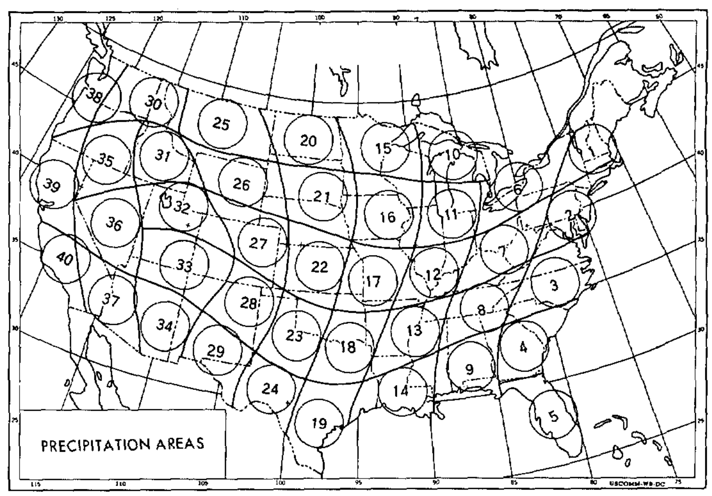

FIGURE 2.—Circles for which the predominating class of precipitation was determined. Each circle is representative of the area bounded by lines. These areas are reasonably climatologically homogeneous.

The above-described charts leave no doubt that the past 4 years represent a major climatic aberration in the United States precipitation regime. These abnormalities pose major problems, not only in terms of water resources, but also for the science of meteorology.

TABLE 1.—*Percentage of normal precipitation 1962–65*

	Winter	Spring	Summer	Fall
New York City	92	58	62	67
Winslow, Ariz.	110	92	119	120
Williston, N. Dak.	101	172	125	90

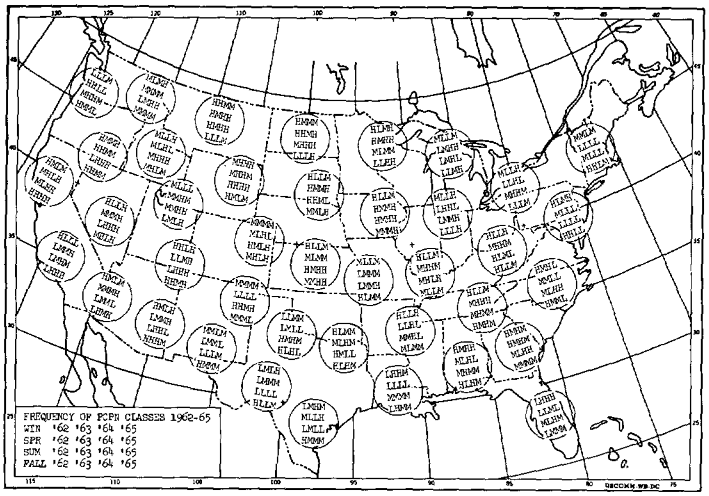

FIGURE 3.—Predominant precipitation classes (light, L; moderate, M; heavy, H) observed during each of the four seasons from 1962 to 1965. Legend in lower left corner of figure.

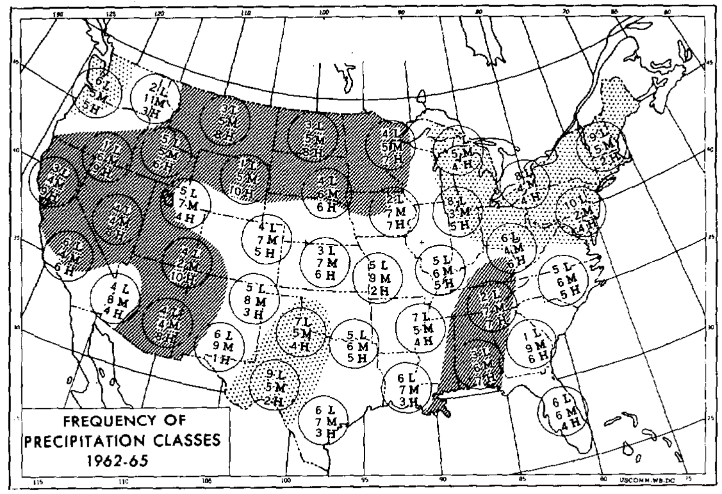

FIGURE 4.—Frequency of precipitation classes (light, L; moderate, M; and heavy, H) for all seasons during 1962–65. Stipled and shaded areas represent predominantly light and heavy precipitation, respectively, while unshaded areas represent predominantly moderate precipitation.

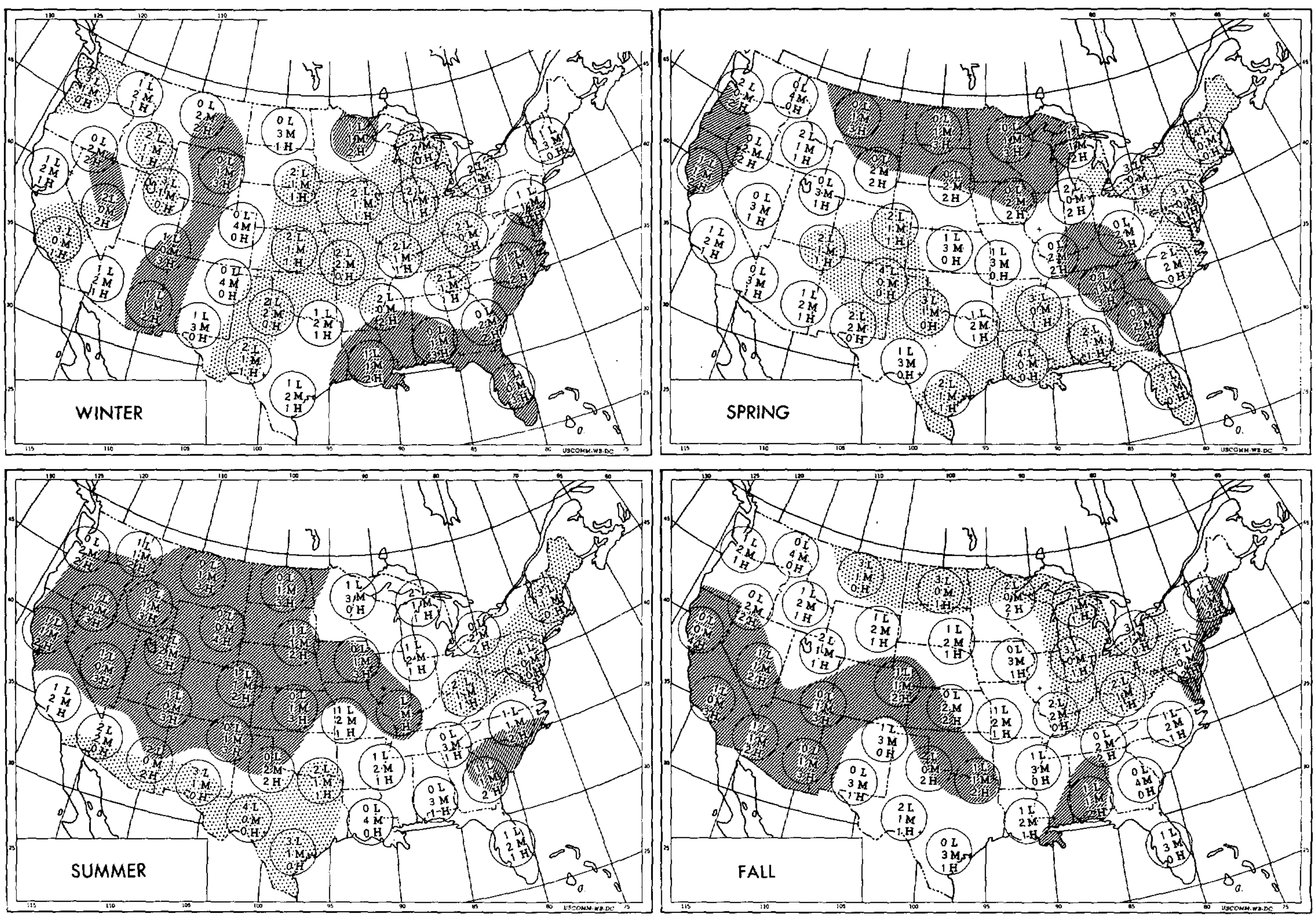

FIGURE 5.—Frequency of precipitation classes during each of the winters, springs, summers, and falls, for the period 1962–65. Shading as in figure 4.

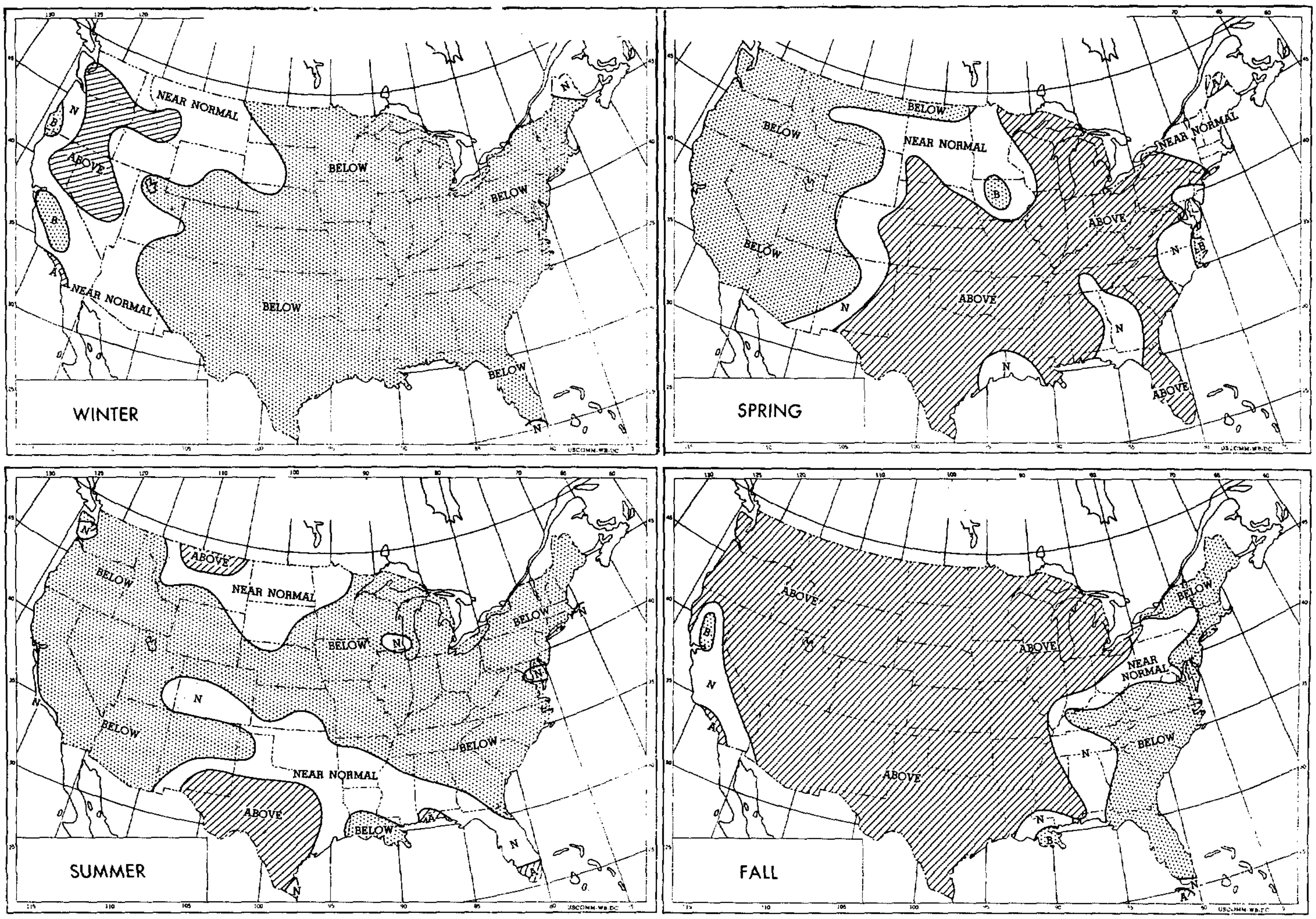

FIGURE 6.—Mean 4-yr. (1962–65) temperature anomaly for each of the four seasons expressed in three categories—below, near, and above normal.

Before we leave the description of recently observed precipitation anomalies, the nature of the contemporaneous temperature fluctuations over the United States should be mentioned. These are illustrated by the seasonal charts reproduced in figure 6, where seasonal temperatures have been analyzed in the three equally likely categories: below, near, and above normal. The ranges or limits for the classes were determined from the long-period climatic records by statistical techniques similar to those used for precipitation. One of the noteworthy things these figures show is the fact that the Northeast drought has been accompanied by essentially cooler than normal conditions rather than warmer than normal ones generally associated with warm-season drought. Also noteworthy is the large areal extent of the predominantly cold air masses over the eastern two-thirds of the country during winters. Later on we shall have occasion to relate these temperature fluctuations and precipitation anomalies to characteristics of the large-scale prevailing air currents of the atmosphere during this 4-year period.

3. ASSOCIATED ATMOSPHERIC CIRCULATION PATTERNS

If successive daily maps are averaged for a week, a month, or a season, undulations in the upper-level westerlies do not vanish. In addition to the normal seasonal variations in the strength of the upper-air currents and in the migration of the principal band of the westerlies, there are also important irregular non-seasonal variations. In order to bring out these non-seasonal variations, the long-term normal contour pattern for a given month may be subtracted from the observed monthly average pattern for the corresponding individual month, and in this way a series of isopleths which show deviations from normal may be constructed. Of course, this procedure may be carried out for a season or for several seasons. An example of such an average chart for the 4 years from 1962 to 1965, together with the isopleths of deviation from normal, is shown in figure 7.

The waves or cyclones along the polar front interact with the planetary waves. If, on a mean map a pro-

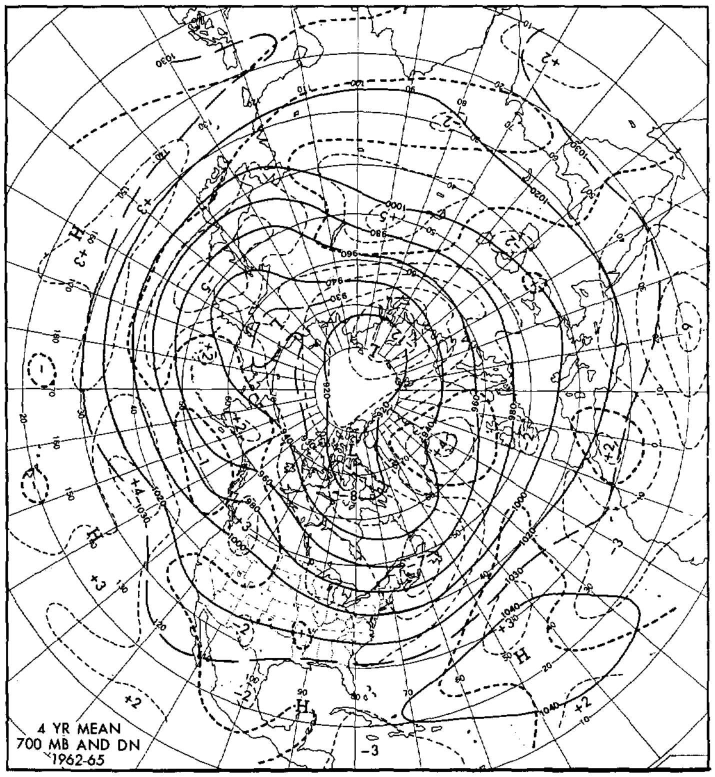

FIGURE 7.—700-mb. contours (solid lines labeled in tens of feet) and isopleths of departure from normal (broken lines with centers labeled in tens of ft.) for the 4-yr. mean 1962–65.

nounced planetary trough is found in a given area, it is likely that this area was subject both to a prevailing temperature contrast from west to east and to frequent intensifying cyclones; and if the trough is anomalously deep (as suggested by negative anomalies), the cyclonic activity is apt to have been more frequent and stronger than normal. The anomalous components of the wind may be inferred from the isopleths of anomaly in the same manner as the total wind may be inferred from the contour surfaces. The above statements follow from numerous extended forecasting studies carried on over the past 20 years [2].

Let us now examine the charts showing the prevailing flow of air and its anomalous components for the 4-yr. period as well as for each of the four seasons, and, if possible, relate these to the general precipitation patterns described earlier. The mean upper-level flow pattern and its departure from normal for the entire 4 years 1962–65 is shown in figure 7. The isopleths of deviation from normal (the broken lines) in this figure bring into focus the dominance of a stronger than normal trough off the Eastern Seaboard of the United States extending northward to Newfoundland. From the rule on the relation between the isopleths of anomaly and the anomalous component of the upper-level winds, it is clear that over much of the Northeast the prevailing anomalous component of air flow was from the northwest. A partial verification of this rule is indicated in table 2 where the resultant winds over Washington, D.C., during the period 1962–65 are shown along with the resultants for an earlier and longer period 1946–55. The seasonal breakdown of these shows that this tendency was especially pronounced during the spring and fall, while the winter and summer had slightly more southerly components than the longer control or more normal period.

TABLE 2.—*Resultant winds at standard levels over Washington, D.C.*

	950 mb.		850 mb.		700 mb.		500 mb.	
	Dir.	Speed (kt.)	Dir.	Speed (kt.)	Dir.	Speed (kt.)	Dir.	Speed (kt.)
WINTER								
1962–65	286°	10	281°	19	268°	31	265°	52
1946–55	280°	10	285°	17	270°	29	265°	49
SPRING								
1962–65	296°	8	290°	15	279°	22	277°	35
1946–55	275°	6	280°	14	276°	23	278°	35
SUMMER								
1962–65	295°	6	293°	9	276°	15	277°	21
1946–55	298°	3	299°	8	296°	13	285°	19
FALL								
1962–65	306°	6	300°	10	279°	15	275°	22
1946–55	281°	4	282°	10	263°	18	258°	30

The influence of the abnormal wind patterns on the upper-air structure over the Northeast is brought to light by average temperatures and dew points at Washington, D.C., for each of the four seasons of the four years, 1962–65, again compared with those for the longer period 1946–55. These values for standard levels are displayed in figure 8. It is at once clear that for all seasons the average lapse rate in the lower troposphere (below 700 mb.) was more stable and the air appreciably dryer than normal. The greatest stability relative to normal was in spring, the period of greatest and most consistent precipitation deficiency and also the time when the anomalous north wind component was especially pronounced. Some idea of the relative dryness of the air column from surface to 700 mb. is indicated by table 2 which shows the average specific humidities at various levels and seasons as well as the total precipitable water in the lowest layers of the atmosphere up to 700 mb. over Washington for both the drought period and the longer control period. These wind, temperature, and humidity data indicate that the Northeast area was characterized by frequent subsiding large-scale air motions inhibiting precipitation. The anomalous wind pattern also indicates that storms frequently moved northeastward *off* the Atlantic Seaboard and intensified east of Newfoundland, a fact verifiable from observed storm tracks over the period [3].

The excess northwesterly flow aloft with respect to

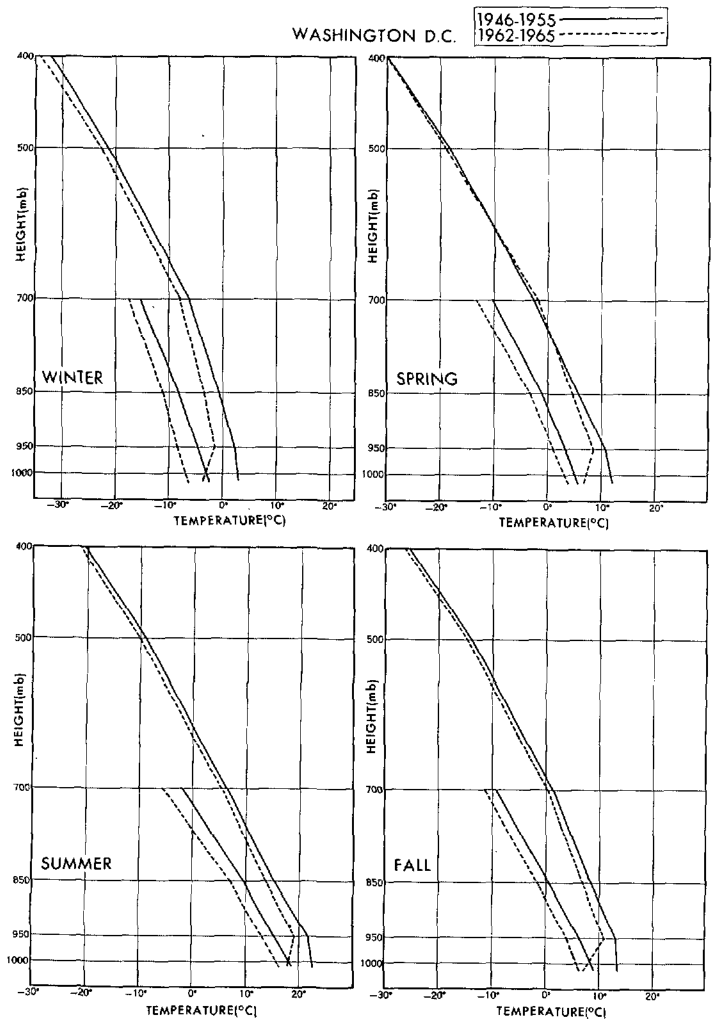

FIGURE 8.—Mean lapse rates of temperature and dew point at Washington, D.C., for the 4-yr. period 1962–65 (broken lines) and for the period 1946–55 (solid lines). Means are for 1200 GMT soundings.

normal also had an effect on the temperature of the Northeast as may be seen in the temperature anomalies for the various seasons shown in figure 6. Thus the frequent advection of cold air from Canada provided prevailingly below normal temperatures as well as deficient precipitation. Consequently the Northeast dry period was a cool, not a warm drought.

On the other hand, over the Southwest the pronounced trough in figure 7 was associated with more than the normal cyclonic and frontal activity and with frequent ascending motion of air leading to adiabatic cooling, condensation, and enhancement of precipitation.

The configuration of anomalies associated with the Southwest trough also implies greater than normal downslope air motion over the Southern Plains, giving the "rain shadow" noted over west-central Texas. The anomalous components of the upper-level winds by seasons (fig. 9) show that the abnormal development of the east coast trough was most pronounced in the spring and summer, to a lesser extent in fall, and least of all in winter. These facts are associated with the predominant precipitation classes indicated seasonally in figure 5, where it is seen that the springs and summers of the past four years have been especially dry over the Northeast, but not the falls and winters.

As for the Southwest, it is apparent from figure 9 that the cyclonic curvature was especially pronounced in winter and spring but less so in summer and fall. These observations may at first glance appear to conflict with the precipitation class frequencies shown in figure 5, where the summers and falls were characteristically wet over the Far Southwest. However, precipitation over the Far Southwest in the warm season usually arises in connection with moist currents emanating from the Gulf of Mexico and Caribbean which are stirred by thunderstorm convection over the Mexican mountains before entering the United States. Moisture is more easily released in showers which form in these "moist tongues" if fronts of cooler Pacific air advance from the west and assist in forcing ascent. This appears to have occurred in the 4-yr. period and is suggested by the relatively cool air over California and the Far Southwest shown in figure 6.

The heavy precipitation over the Northern Plains which characterized the springs and summers and to a lesser extent the winters was associated with forced ascent of the moist upper-level air currents arriving from the southwest over cooler air currents arriving chiefly from the Pacific.

In summary, we see that the broadscale precipitation characteristics over much of the United States may be related to prevailing wind patterns aloft and particularly to their anomalous components, even though the averaging process is spread out over periods of 4 months or even 16 months.

Before leaving the subject of anomalous flow, we may gain valuable insight by examining the profiles of height anomaly observed during each of the 4 years along latitude 40° N. These graphs, in which height anomaly is plotted against longitude from Greenwich westward to 180°, are shown in figure 10. Here it is clear that the east coast negative anomaly (the anomalous trough), which showed up so clearly in the 4-yr. mean of figure 7, is also revealed in the annual averages for each of the 4 years 1962–65. This anomalous trough has been indicated as a double open line and, to illustrate its quasi-permanent position along and off the east coast, the area from 50° W. to 70° W. longitude has been shaded. No similar repetition of a singular anomaly exists at other longitudes during this 4-yr. period.

4. POSSIBLE CAUSES

Thus far in this report I have attempted to point out salient features of the 1962–65 climatic fluctuations over the United States and relate these to the contemporary upper-level wind patterns and the implied storm tracks and air masses. Such relationships should not be mis-

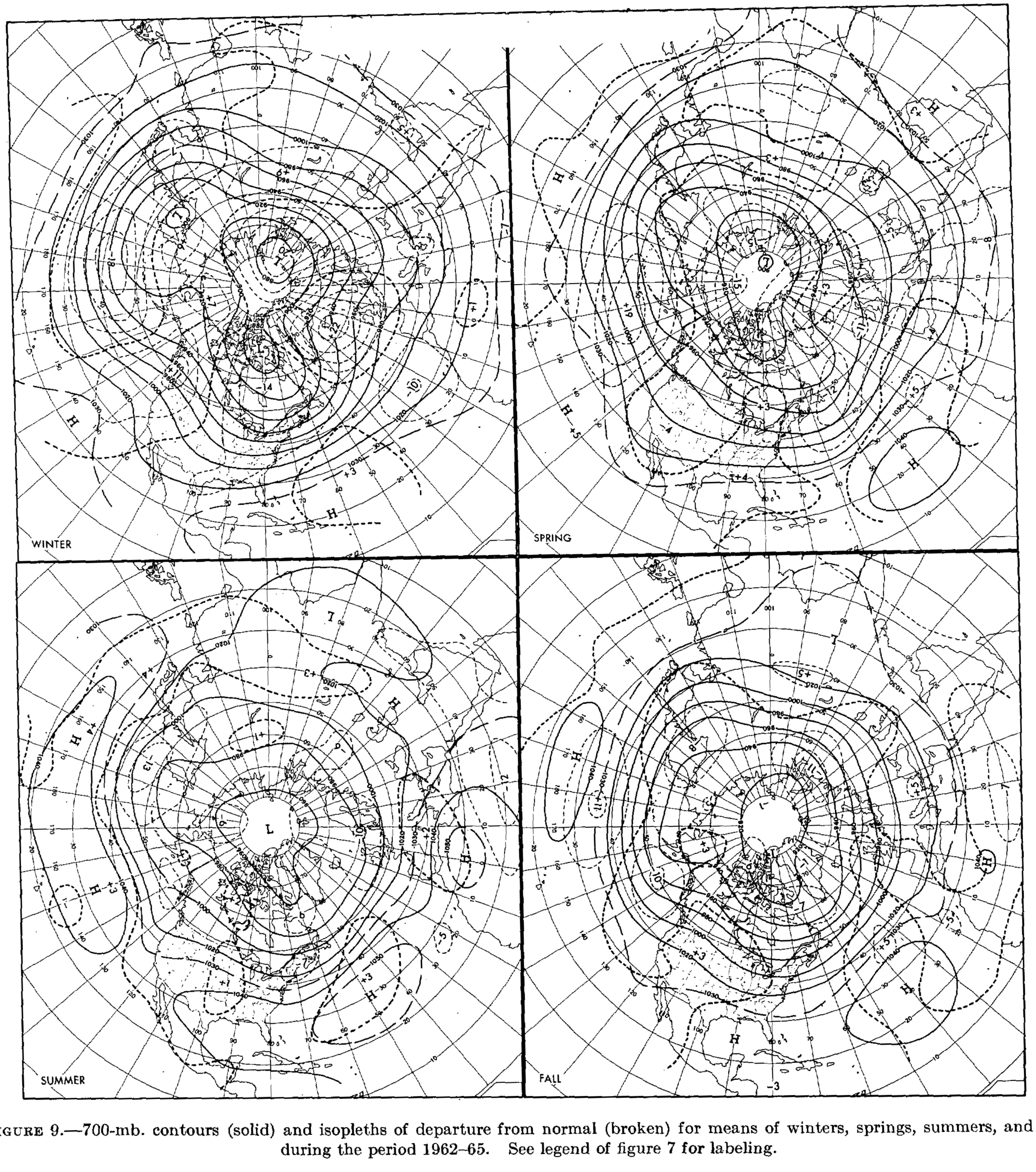

FIGURE 9.—700-mb. contours (solid) and isopleths of departure from normal (broken) for means of winters, springs, summers, and falls during the period 1962–65. See legend of figure 7 for labeling.

taken for *causes*, for the question of how the abnormal wind patterns arose and were maintained over such a long period remains. At the very start it must be made clear that meteorologists and climatologists do not have satisfactory solutions to these problems; for this reason long-range predictions for time intervals beyond a month or season have not been considered possible by the scientific community.

The reason for this undesirable state of affairs resides primarily in the fantastic complexity of atmospheric behavior. It seems that interdependence on all time and space scales is one of the characteristic features of the atmosphere. Everything seems to depend on everything else in a non-linear manner.

To begin our hypothesis, since the sun is the primary source of heat for driving the atmospheric motions, it is obvious that the normal wind patterns will vary with time of year. Thus, observed wind patterns for 30 March

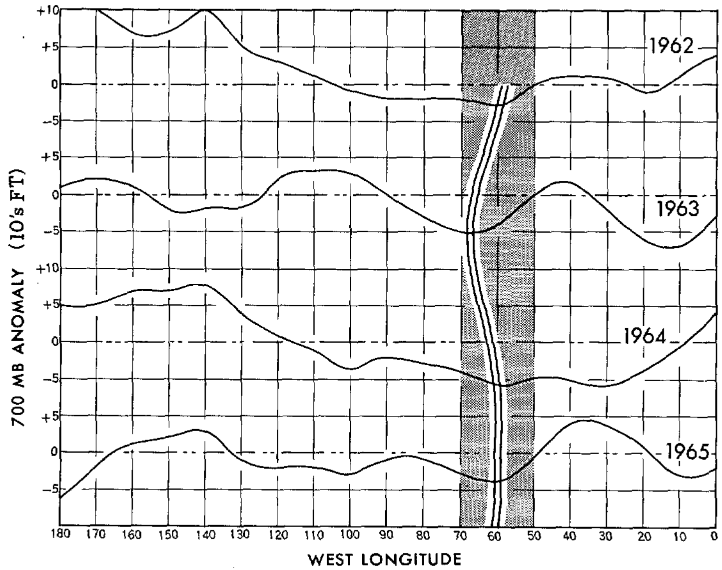

FIGURE 10.—Mean departures from normal of the height of the 700-mb. pressure surface in tens of feet at 40°N. for each of the 4 years 1962–65. Shaded area embraces the persistent anomalous trough off the Eastern Seaboard of the United States. Trough line is indicated by double line.

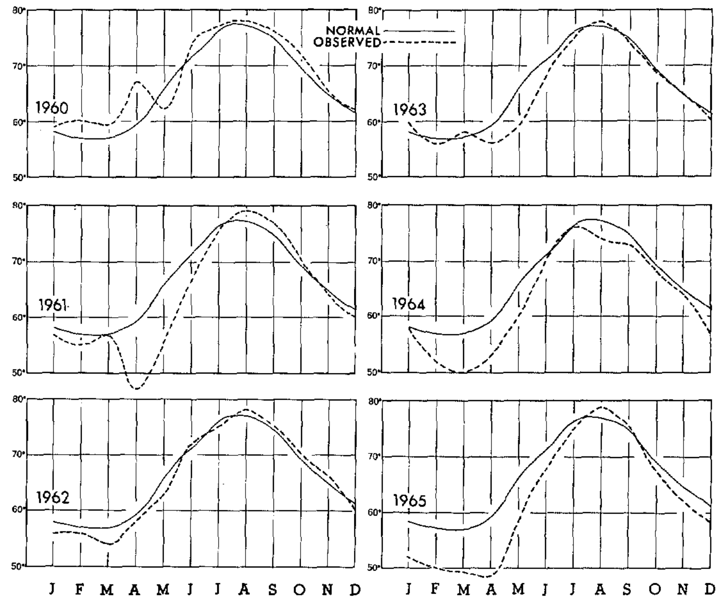

FIGURE 11.—Mean sea-surface temperature (dashed line) within a 3° (lat.) diameter circle centered at 37.5°N., 72.5°W. for each month of the years 1960–65. Solid line represents long-term normal.

months will differ appreciably from those for 30 Aprils. In the second place, even though geographical features of the globe are fixed, there are sizeable variations in characteristics of the land and water surfaces in the same season of different years. For example, temperatures of the surface waters of the ocean are now known to undergo fluctuations of several degrees F. between the same month of different years [4]. These variations in ocean temperature are broadscale, so that water temperature anomalies of 3° to 6° existing over areas as large as the United States may frequently be found in the Pacific [5]. Furthermore, the areas of the continents occupied by ice and snow during winter also vary between winters. Finally, during the warm season the surfaces of continents vary with respect to soil moisture so that marginal areas may frequently be dry for a few years and then wet for a number of years. All these external boundary effects influence atmospheric behavior via the radiation received from the sun and emitted from the land and modify the heat and moisture extraction from land or continent. One of the great difficulties is that the precise influence of these variable boundary conditions on the overlying atmosphere depends on the characteristics of the atmosphere itself (that is, its regional positioning of air masses, storm tracks, etc.). Thus the effect of an abnormality in oceanic temperatures, soil moisture, or snow and ice cover will be different according to the form of the general wind and weather systems.

We have omitted mentioning variations in the sun's radiation, although it is conceivable that these external effects may also disturb the atmospheric circulation. This omission was purposeful because of the controversial nature of this subject and because of the lack of acceptance by the meteorological profession of alleged solar-weather relationships. While it appears that meteorologists are more likely, instead, to agree on the influence of earth-atmosphere boundary variations, the relative importance of these variations has not been conclusively established.

In such problems where multiple causes operate, one cannot choose a definite starting point for his reasoning. The point of departure is arbitrary since all phenomena are interactive. We shall begin by describing some aspects of the water temperatures observed during this period off the Eastern Seaboard and interrelate these with the abnormal atmospheric circulation. We shall then proceed to do likewise with some anomalous conditions observed during the same four years over the North Pacific. Finally, we shall try to knit together a plausible theory.

One of the most striking abnormalities of water temperature observed anywhere during the drought period of the Northeast has been the presence during roughly the first 6 months of the year of colder than normal water along the Atlantic shelf from Virginia northward. This is illustrated in figure 11 where observed average monthly mean sea-surface temperatures in a circle of 3° lat. diameter (about 200 mi.) centered at 37.5° N., 72.5° W., a point about 150 mi. off the Delaware coast, have been plotted against the normal for each of 6 recent years.[1] Note that colder than normal water was produced during

[1] All ship observations of sea-surface temperature within this circle were averaged according to month. The usual number of observations making up such a monthly average is about 180, and these are fairly evenly distributed within the circle.

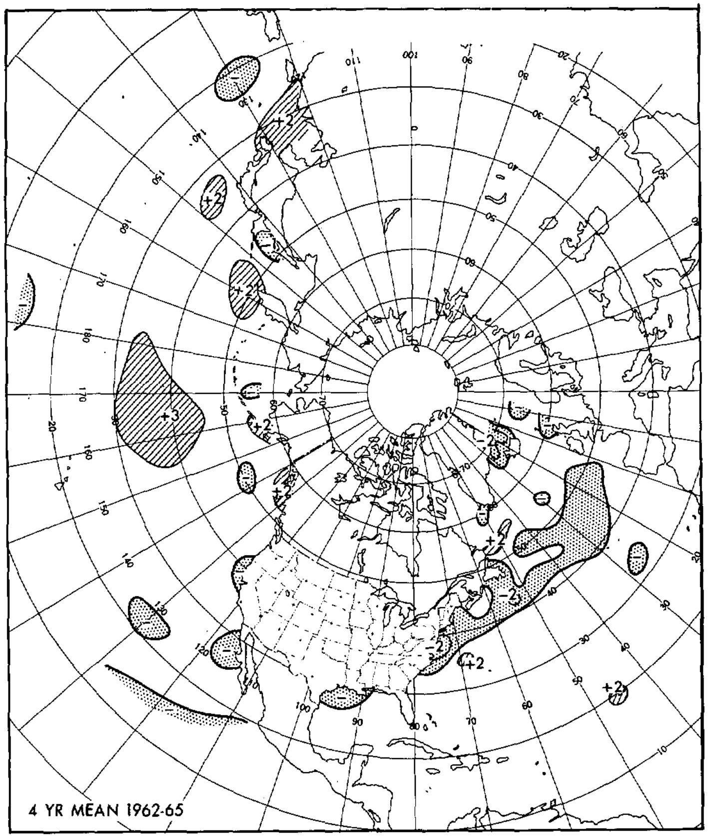

FIGURE 12.—Departures from normal of sea-surface temperature (°F.) for entire 4-yr. period 1962–65. Stippling indicates below normal; shading, greater than 2°F. above normal.

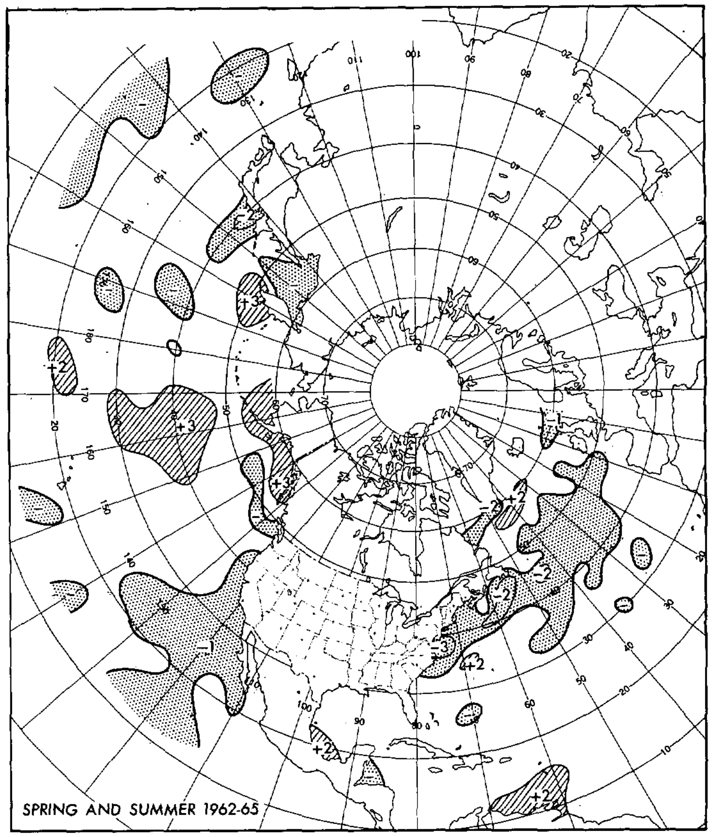

FIGURE 13.—Departures from normal of sea-surface temperature for the combined springs and summers of the period 1962–65. Shading as in figure 12.

each winter in this area, beginning in 1961; that the water reached maximum relative coldness in spring; and that these abnormalities have amplified more recently. This circular area surrounding 37.5° N., 72.5° W., is part of a large pool of cold water observed to prevail in the 4-yr. mean (fig. 12) and in the mean for spring and summer (fig. 13).

The cooler than normal water extended only for some 400 or 500 mi. off the United States Atlantic Seaboard, while to the east sea-surface temperatures were slightly above normal. Thus the horizontal gradient of sea-surface temperature anomaly off the Middle Atlantic States was increased in the average by some 4° F. for the entire 4-yr. period 1962–65 and by 5° F. during spring and summer. In the spring of 1965, the dryest of the four springs in the drought area, this gradient exceeded the normal by over 11° F. The above observations should be borne in mind when treating the influence of the ocean upon atmospheric circulation, because the ocean water transfers its heat rapidly to the overlying air. Moreover, such sea temperature abnormalities are not confined to a shallow layer but often are characteristic of the mixed layer down to 100 or 150 ft. below the surface.

Before discussing sea-surface temperature anomalies in other areas of figures 12 and 13 we shall say something about the production and maintenance of this pool of cool water off the Atlantic Seaboard.

From our earlier discussion it will be remembered that the air masses leaving coastal areas north of Cape Hatteras were prevailingly colder than normal during most of the 4-yr. period (see fig. 6). These air masses were appreciably drier than normal, too, as is indicated by the precipitation pattern (fig. 5) and by observations of humidity obtained with the help of aerological soundings (fig. 8). For example, the moisture in a kilogram of air at the 2000-ft. level over Washington, D.C., averaged about 4 gm. compared with 5 gm. normally observed during spring (table 3). Similar moisture deficiencies were observed in the 4-yr. averages for each season. Thus the cooler and drier than normal air masses, when advected off the Atlantic Seaboard, received a greater transfer of sensible and latent heat than normal from the ocean. Computa-

TABLE 3.—*Specific humidities in gm./kg. at standard levels, and precipitable water in columns up to 700 mb. (1962–65 and 1946–55 periods)*

	Winter		Spring		Summer		Fall	
	1962–65	1946–55	1962–65	1946–55	1962–65	1946–55	1962–65	1946–55
Surface	2.4	3.1	5.1	5.7	11.4	13.2	6.1	7.3
950 mb	2.1	2.8	4.3	5.1	9.8	11.3	5.4	6.3
850 mb	1.9	2.4	3.4	4.1	7.2	8.7	4.0	4.7
700 mb	1.4	1.6	2.0	2.5	3.5	4.5	2.3	2.7
Precipitable water (in.)	0.23	0.30	0.43	0.51	0.92	1.09	0.52	0.61

tions of the heat loss from a surface layer of water of 50 m. depth off the east coast were made by using the following mean data for the four winters of 1962–65 and for the long-term normal:

a. the geostrophic wind speed and sea-surface temperature at 37.5° N., 72.5° W.

b. the air temperature, relative humidity, and cloudiness at three stations along the Atlantic Seaboard over which most of the continental air passes on its way to the waters off the mid-Atlantic coast.

From these data the sensible and latent heat loss as well as the gain or loss through short-wave radiation absorption and long-wave radiational cooling were computed by empirical bulk formulas [6]. The results of these computations are shown in table 4 from which it is seen that an average temperature deficit of about 1.3° F. relative to normal would be achieved at the end of the winter season. Similar calculations for other seasons show even greater heat losses (about 3° F.) in fall, no loss in spring, and some heat gains (almost 2° F.) in summer. These computations are especially interesting in view of figure 11, which shows that the anomalous fall of sea-surface temperature took place mainly in fall and winter, while the anomalous rise occurred in summer.

It therefore appears that anomalous atmospheric conditions were partially responsible for the cooler than normal pool of water—and particularly for its maintenance.

It is quite probable that the very atmospheric conditions responsible for maintaining this cool water were also generated by some of the anomalous water conditions—particularly the anomalous gradient of sea-surface temperatures referred to earlier. We shall now suggest the means by which this may have come about. In the first place, once the oceanic temperature gradient has been established off the Atlantic Seaboard, as indicated in figure 12, less heat is transferred into the air masses which follow behind cold fronts and more heat than normal is transferred to the warm air masses moving over and to the east of the Gulf Stream in advance of the fronts. Such heat transfer into the air is known to take place rapidly, so that the gradient of temperature in the air is increased. This increased horizontal temperature contrast, carrying with it increased baroclinicity, intensifies cold fronts and tends to strengthen the wave disturbances (nascent cyclones) which frequently develop off the east coast. This intensification of fronts and cyclones a few hundred miles off the Eastern Seaboard naturally plays a more important role in spring and summer than during winter when the temperature contrast between continent and ocean is overwhelming. It may be shown from the storm tracks observed during the springs and summers of these 4 years as well as from the mean upper-air patterns (see fig. 9) that this type of boosted development did indeed occur [3]. Fronts sharpened in this area and nascent cyclones developed more strongly farther out to sea than they usually do as they moved northeastward

TABLE 4.—*Seasonal temperature changes (°F. per season) in top 50 m. of water at 37.5° N., 72.5° W. (winters of 1962–65)*

	Sensible	Latent	Short-wave radiation absorption	Long-wave net cooling	Sum
Atlantic City:					
Seasonal	−10.0	−12.6	6.3	−8.8	−25.1
Normal	−8.9	−12.1	6.3	−9.0	−23.7
Departure from normal	−1.1	−0.5	0.0	+0.2	−1.4
Philadelphia:					
Seasonal	−10.8	−13.1	6.2	−9.9	−27.6
Normal	−9.8	−12.4	5.9	−9.7	−26.0
Departure from normal	−1.0	−0.7	+0.3	−0.2	−1.6
New York:					
Seasonal	−10.1	−13.2	6.8	−10.0	−26.5
Normal	−9.6	−12.4	6.5	−10.1	−25.6
Departure from normal	−0.5	−0.8	+0.3	+0.1	−0.9

toward Newfoundland. The greater than normal development of these cyclones off the coast in turn led to the flow of dry cool air masses from the north and northwest over the drought-plagued area. The area of cyclone development was sufficiently removed from the east coast that most of the precipitation from the storms fell at sea rather than over land areas where it was needed.

Another factor limiting the warm-season precipitation is the low-level cooling imposed by the cool ocean on air currents arriving from the south ahead of cold fronts. This cooling leads to increased vertical stability and makes it more difficult for cold fronts to force aloft the warmer air ahead of them. It also inhibits air mass convective activity.

All these phenomena are implied by the charts displayed earlier in this report. However, the fundamental question arises as to how the cool pool became established off the Eastern Seaboard in the first place. We note from figure 11 that some of it was already generated during the winter and spring of 1961 and 1962. However, the dryness over the Northeast did not set in until the fall of 1961.

Another factor besides heat transfer from water to air may have played a role in producing colder than normal water off the Atlantic Seaboard, particularly in 1961 and 1962. It is possible that increased transport of cold Labrador water southward along the North American coast was brought about by the predominance of favorable surface wind stresses on this water. While we are not able to document the cold water transport, the sea level pressure distribution during 1961 and 1962 (not shown) is quite similar to a case in 1959 when Worthington [7] on an oceanographic survey south of Nova Scotia found a deep and horizontally extensive current of appreciably colder than normal water. Thus it is quite possible that the advection of cold Labrador water in 1961 set the stage for the complex series of interdependent events in the atmosphere and ocean which took place then and subsequently.

We shall now say a few words about the extensive cold air masses which penetrated into the eastern half of the United States during the winter (fig. 6), because these cold air masses leaving the east coast were in part responsible for initiating the steep decline of water temperatures which took place during the winters (fig. 11). In the first place, these cold air masses were driven southward from the Arctic and from Canada by the combination of an anomalously strong ridge along western North America (see fig. 9). This amplified wave pattern over North America may have been a response to events in the central Pacific. That is, stronger than normal cyclonic (and thus upper-level trough) activity there (indicated by the large negative anomaly of −180 ft. in fig. 9) usually causes inertial (barotropic) reactions downstream which generate both a strong ridge along the west coast and a strong trough to the east. Once the cold polar air had been driven southward to the Gulf coast, wave cyclones developed along its front and these cyclones—since the air masses in their advance were so cold—frequently produced snow over the eastern part of the Nation. While the snow occupied the surface it served to refrigerate further the southward-moving cold air masses and thus strengthen the temperature gradients along the Gulf and east coast—gradients on which the storms fed. Of course, this refrigerated air also removed heat from the waters off the Atlantic Seaboard.

Studies of special cases of winter activity during this period by the author [8] suggest that the upstream cyclonic activity over the central Pacific proposed as a cause of the unusual polar outbreaks over the eastern United States may have been stimulated by the extensive pool of water of appreciably warmer than normal temperatures north of Hawaii (fig. 12). There, in contrast to the excitation produced off the Atlantic Seaboard by an enhanced gradient of sea-surface temperature, the stimulation of cyclonic activity may have been provided by the increased transfer of heat and moisture from the sea as very cold air masses moved into the area from Asia and the Bering Sea.

5. SUMMARY

The facts brought to light by this investigation reveal that the 1962–65 drought over northeastern United States was chiefly confined to spring and summer and was associated with prevailingly below normal temperatures during all seasons. While dryness prevailed over the Northeast, abundant rainfall was observed during the quadrennial over the Far Southwest and the Northern Plains.

The prevailing circulation patterns for this 4-yr. period involved an anomalously deep mid-tropospheric trough, especially pronounced during spring, just off the Atlantic Seaboard. This, in turn, was associated with resultant winds both at surface and mid-troposphere possessing a greater northerly component than normal. This circulation pattern was also associated with more than normal cyclonic activity, frontogenesis, and cyclogenesis off the Atlantic Seaboard, and early occlusion off Newfoundland. The anomalous northerly components were associated not only with below normal temperatures but also with subsidence and dryness, reflected in the seasonal means of aerological soundings.

The above *description* of anomalous events obviously calls for an explanation. It is suggested that anomalously cold surface water along the Continental Shelf, by interacting with the overlying atmosphere, assisted in stabilizing the drought pattern. It may have done this in two principal ways: (1) by accentuating the atmospheric baroclinicity along the eastern boundary of the cold water, thus providing a mechanism for increased frontal and cyclonic activity favoring early occlusion, and (2) by providing a source for low-level cooling (increased static stability) of air masses arriving ahead of cold fronts, thereby inhibiting precipitation over the land areas.

The recurring abnormal atmospheric circulation described above would provide a means of extracting more heat than normal from the offshore water, since the air masses were dryer and cooler than normal over the fall, winter, and spring. Some rough (bulk method) calculations suggest this was an important factor in the maintenance of cold water. The initial cold water, however, may have resulted from a strengthened flow of Labrador water as early as 1961, although this is only an inference drawn from analogy.

Thus the climatic fluctuation in precipitation in the United States during the four years 1962–65, of which the Northeast drought is the most spectacular part, appears to be due to multiple and interlocking causes. Evidence suggests that the abnormal weather patterns have been related to abnormal hemispheric wind patterns in layers of the atmosphere extending from the surface to the mid-troposphere and probably much higher. These abnormal wind patterns have produced systematic variations in the thermal characteristics of the earth's surface, especially in the surface waters of the oceans, and these may have led in turn to reinforcing (feedback) effects on the abnormal circulation of the overlying atmosphere, thereby perpetuating the abnormal weather. While a break in the cycle is likely, meteorologists do not understand these complex phenomena sufficiently to indicate when this break might occur. Furthermore, a great deal more quantitative work will be necessary to verify the causal hypothesis. An attempt to do this with the help of physically-based concepts and high-speed electronic computers is proceeding [9].

APPENDIX

When adequate historical records of sea-surface temperature become available it may be possible to examine more completely the statistical validity of the hypothesis set forth in this paper. Then we may seek answers to these questions: Have earlier periods when colder than normal water predominated off the Atlantic Seaboard for a few years been associated with deficient precipitation over the Northeast? Have periods of abundant precipitation been associated with warmer than normal water?

In order to obtain a partial answer to the latter question, the record of precipitation since 1941 at La Guardia Field, N.Y., was examined and the three years with greatest precipitation were selected—1951 with 51.40 in., 1952 with 51.35 in., and 1953 with 51.15 in. The mean

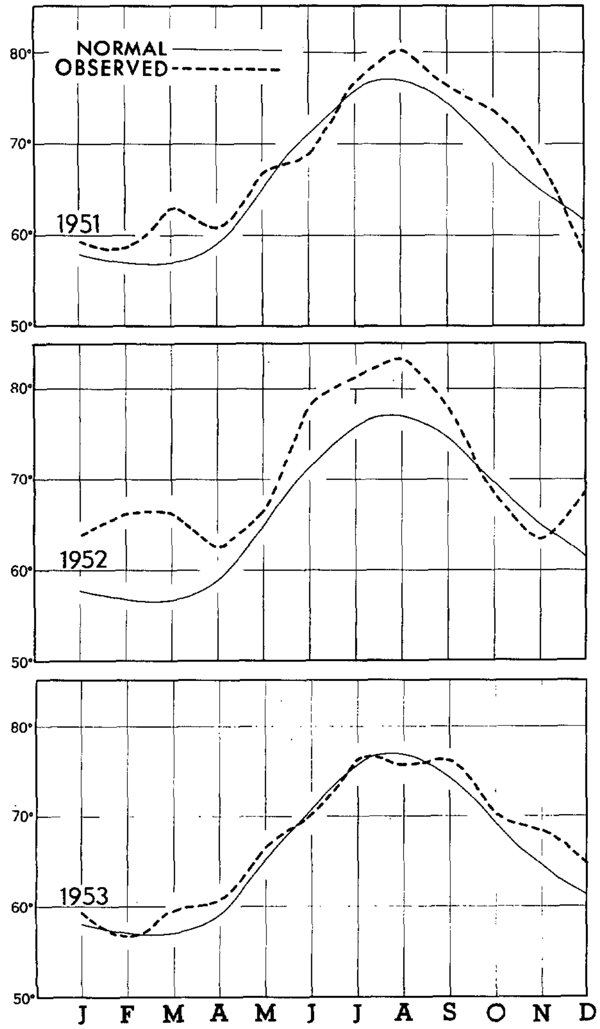

FIGURE 14.—Mean sea-surface temperature (dashed line) within a 3° (lat.) diameter circle centered at 37.5°N., 72.5°W., 1951, 1952, and 1953. Solid lines represents long-term normal.

for the period 1941–65 was 42.42 in. By comparison, the years 1963, 1964, and 1965 were the driest three in the record, with precipitation totals of 31.77, 31.31, and 22.17 in., respectively.

Sea-surface temperatures for the area surrounding 37.5° N., 72.5° W. were taken from 1200 GMT data on the Synoptic Weather Maps, Part 2. The monthly means for each of these three years (1951–53), along with the long-period normal, are shown in figure 14, to be compared with figure 11 of the main text. The number of observations per month averaged many fewer than the 180 obtained in the later years (e.g., 13 in 1951, 16 in 1952, and 71 in 1953), which may account for some of the irregularity of the observed graphs of sea-surface temperature. Nevertheless, one can conclude from figure 14 that the surface water of the 1951–53 period was indeed warmer than normal. It is also noteworthy that the spring precipitation for each of these years totaled 15.00, 17.49, and 19.16 in. compared to a mean for the whole 1941–65 period of 11.13 in., and a mean for the dry 1963–65 period of only 6.79 in.

Apparently the association of precipitation with sea-surface temperature off the Atlantic Seaboard is similar to that found by Priestley [10] off the New South Wales coast of Australia.

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